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13. ABSTRACT *(Maximum 200 words)*

Hybrid optics are optical systems that integrate diffractive optical surfaces into lenses, resulting in designs that minimize aberrations, reduce the cost, weight, and complexity of the system, while improving the overall optical efficiency. In the Phase I STTR program described in this report GELTECH, Inc., and the Oak Ridge National Laboratory successfully demonstrated the feasibility of producing just such a diffractive/refractive hybrid optic in silica glass by a replication process which lends itself to high volume, low cost production.

The technical objectives accomplished in Phase I were: 1) design and numerical modeling of a hybrid diffractive/refractive optic, 2) fabrication of the optic master using diamond turning, 3) design and fabrication of optical molds, 4) fabrication of silica glass prototypes, and 5) characterization of the prototypes for replication accuracy and optical performance

Potential applications of hybrid optics include military, space, and high radiation applications, and consumer and medical products.

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Final Technical Report

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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LIST OF PUBLICATIONS

1) "Hybrid optics for the visible produced by bulk casting of sol-gel glass using diamond-turned molds", B.E. Bernacki, A.C. Miller, L.C. Maxey, J.P. Cunningham, W.V. Moreshead, and J.L. Noguès, Presented at SPIE Conference in San Diego, CA, July, 1995.

2) "A silica glass hybrid singlet produced by sol-gel replication and single point diamond-turned mold", B.E. Bernacki, A.C. Miller, L.C. Maxey, J.P. Cunningham, W.V. Moreshead, and J.L. Noguès, to be presented at the meeting of The Optical Society of America in Portland, Oregon, September, 1995.

EXECUTIVE SUMMARY

The Phase I research effort targeted the design and fabrication of a hybrid diffractive/refractive optical element in silica glass by means of a replication process. **That work has resulted in the successful production of prototypes of a single element, single glass hybrid optic which is corrected for both spherical and chromatic aberrations. Because the process for making the optic is a replication process it lends itself to high volume production at relatively low cost.** Figure 1 below shows a photograph of an actual hybrid lens and plastic mold from which it was made. Figure 2 shows a cross section profile and oblique plot of the central transitions of the lens with its facet-like diffractive surface features. Full details of the replication and optical performance of the lenses are given in section 1 following.

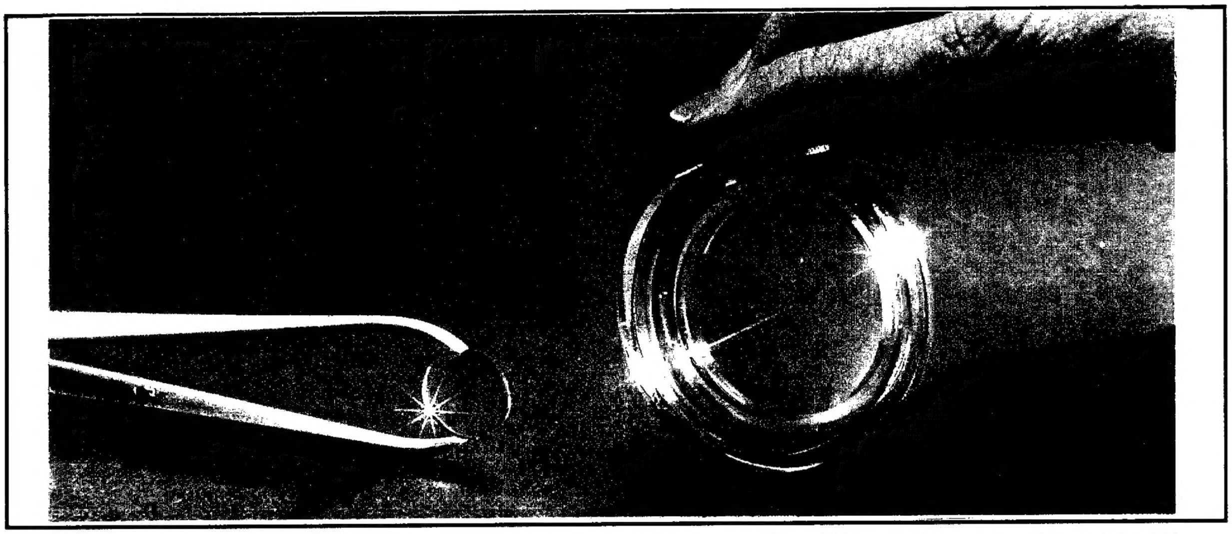

Figure 1: Hybrid Diffractive/Refractive Optical Element in Silica Glass Produced in Phase I, and Plastic Mold Used to Produce It

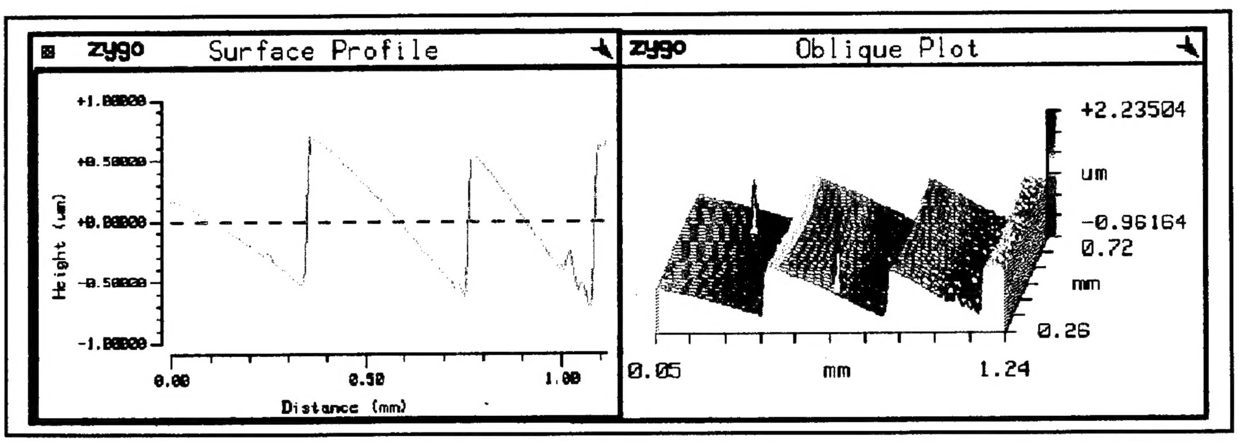

Figure 2: Cross Section and Oblique Plot of the Central Region of the Convex Surface of a Silica Hybrid Optical Element

During the Phase I program the relationship between GELTECH and Oak Ridge has proven to be a very synergistic one: Oak Ridge has outstanding capabilities in optical design, high precision diamond turning, and optical metrology, while GELTECH has expertise in mold

fabrication and a unique process for directly molding complex optical elements in silica glass, one of the best optical materials available. This molding capability provides the potential for translating a single high-precision diamond turned optical element into literally thousands of high quality replicas in a cost-effective manner by mass replication.

The technical objectives of this research effort were:

1) to design and numerically model a hybrid diffractive/refractive optic
2) to fabricate the optic master using diamond turning
3) to design and fabricate the mold
4) to fabricate prototypes
5) to characterize the prototypes

To demonstrate the feasibility of fabricating by replication a glass hybrid diffractive/refractive optic, the above objectives were completed. Figures 1 & 2 show one of the hybrid optical elements produced during Phase I.

Major accomplishments which were made during the course of this research include:

1) The design and numerical modeling of a 1/2" diameter hybrid lens
2) The fabrication of the optical quality master tooling by diamond turning
3) The design and fabrication of plastic injection molds
4) The fabrication of silica glass prototypes by bulk casting using the sol-gel process
5) Characterization of surface profiles of the tooling, molds, and hybrid optics, as well as optical performance testing of the silica prototypes produced.

The successful demonstration of the feasibility of these combined technologies to produce a hybrid diffractive/refractive optic in silica glass was accomplished in Phase I.

The development of a second hybrid optic prototype having a diameter of 5 mm is underway at the present time. The molds are being produced at the present time for casting in the sol-gel process. GELTECH and Oak Ridge National Lab believe strongly in the development of this technology, and in addition to the original statement of work for this program, have decided to pursue a second, smaller optic in an effort to further advance the technology.

A Phase II proposal has also been submitted in which GELTECH and Oak Ridge National Lab propose to develop and fabricate prototypes which, upon completion, will have required the solving of the engineering issues necessary for commercialization of this hybrid optics technology in Phase III.

I. INTRODUCTION

Trends towards miniaturization and the development of new applications are demanding new and better optical elements. These optical elements can include a range of types and designs, such as diffractive or binary [1], hybrid diffractive/refractive [2,3], aspheric [4], and Fresnel [5]. Typical requirements involve new and better ways to shape, collimate, and/or direct light while keeping the optics small, lightweight, inexpensive, yet high in optical efficiency. In some applications the requirements of a new design include an optical material which is more rugged and able to withstand extreme environments. Because the applications in which these elements are required are expected to develop rapidly, it is essential for the U.S. to develop the optics technology concurrently, or the chance for technological leadership will be lost. Furthermore, attaining such leadership will require the development of methods of mass production which can make these optics available at low cost and in high volume, and meet the realistic demands of the marketplace.

The term hybrid optics describes optical systems that integrate diffractive optical surfaces into refractive optics such as lenses. The resulting designs minimize the aberrations that degrade image quality without the need for additional elements and the combination of different types of glass. This reduces the cost, weight, and complexity of the system, while improving the overall optical efficiency. Forming the diffractive surface on a curved base surface provides an extra degree of freedom not currently available in conventional optics for correction of aberrations, making high-performance optical systems better, smaller and cheaper. Hybrid optics are manufactured at present for infrared applications using diamond turning. Continuous form diffractive structures (called kinoforms) are not routinely achieved for visible wavelength applications, because of the very small features required. Applications in the visible are primarily binary approximations of kinoforms produced with photolithographic techniques, and are restricted to planar surfaces. While many designs have been published [1] that take advantage of the combination of diffractive and refractive optical elements in hybrid optical systems, they will remain academic curiosities unless a method of mass producing high-quality hybrid lenses cheaply is developed.

1.1 Benefits of Hybrid Optical Elements

The most immediate benefit of hybrid optical elements that combine refractive and diffractive surfaces is their ease of achromatization. Optical glasses are dispersive, causing their refractive power to vary with wavelength. Diffractive optical elements obey the grating equation, and the angle of the diffracted orders also vary with wavelength. Luckily, however, refractive and diffractive optics have an opposite dependence of the focal point of the lens versus wavelength. If an uncorrected refractive optic is designed to focus at a point determined by the middle wavelength of its design spectrum (yellow for visible optics), blue light will be focused in front of the nominal focal plane, and red light will come to a focus behind the nominal focal plane.

Diffractive optics have the opposite behavior: their power varies directly with wavelength. If diffractive and refractive optics are combined correctly, these two effects will cancel each other reasonably well over the design spectrum, and the focal point will not vary appreciably with wavelength. By combining the diffractive element with a refractive optic having an aspheric front surface, spherical aberration and coma can also be controlled completely using only one single element.

Hybrid optics also provide a method for reducing the effects of temperature in optical systems. Control of the change in focal length and other lens properties with temperature is called athermalization, and can be corrected in a manner similar to achromatization. The benefit offered by hybrid optics is that the opto-thermal expansion coefficient for the diffractive portion of the hybrid optic is a function only of its mechanical properties, such as coefficient of thermal expansion, while the opto-thermal expansion coefficient for the refractive optic is a function of both its mechanical and optical properties [6].

The combination of the diffracting element with a curved, as opposed to a planar, base surface that is made possible by diamond machining permits an additional degree of freedom in eliminating any residual aberrations from the lens. As early as 1973 [7] it was shown that diffractive lenses could be made free from spherical aberration at certain object-image conjugates (aplanatic) if the diffractive element was formed on a spherical surface. This approach has been recognized as a means to achieving additional aberration correction [2,3] and is the subject of many paper designs, but has yet to be routinely demonstrated in a working device due to difficulty in fabrication.

By reducing the number of elements in complex lens systems, and combining the aspheric surface and diffractive element on the same lens blank, manufacturing costs are reduced due to fewer alignment steps, and fielded systems are more tolerant of environmental effects, such as shock and vibration. An example of a wide field-of-view eyepiece is reproduced in Figure 3 from Ref. 8 to show the improvements possible using hybrid optics. The all-refractive design at the top requires 8 elements to achieve its design goal, while the hybrid eyepiece shown in the bottom of the figure needs only five, and exceeds the optical performance of the all-refractive design.

1.2 Advantages of Diamond Turning for the Manufacture of Hybrid Optics

Hybrid optical systems consisting of refractive and diffractive elements with excellent diffraction efficiencies are now being fabricated using the technology offered by stepped binary optics [9]. The diffractive surface for the hybrid element is formed on a planar base surface of the refractive element using multiple masks (depending on the binary levels desired) and step-and-repeat photolithographic methods to approximate a continuous kinoform with a staircase or binary profile. This is followed by reactive ion etching to obtain the desired phase profile. Because of the need to image the mask onto the optical surface at the correct magnification and aspect ratio, base surfaces are limited to planar using this method. Furthermore, alignment of the separate diffractive and refractive surfaces within a single optical element is not trivial.

With diamond turning, on the other hand, a continuous phase profile (kinoform) is directly machined onto the optical surface in one step. With hybrid optical elements, the design strategy is to assign most of the power to the refractive surface, while letting the diffractive surface correct for aberrations such as chromatic or spherical aberration. This approach greatly relaxes the number of phase zones that must be cut into the surface of the lens, and makes it possible to diamond turn a high quality kinoform surface [10]. A profile of a kinoform element compared with a typical refractive surface is shown in Figure 4.

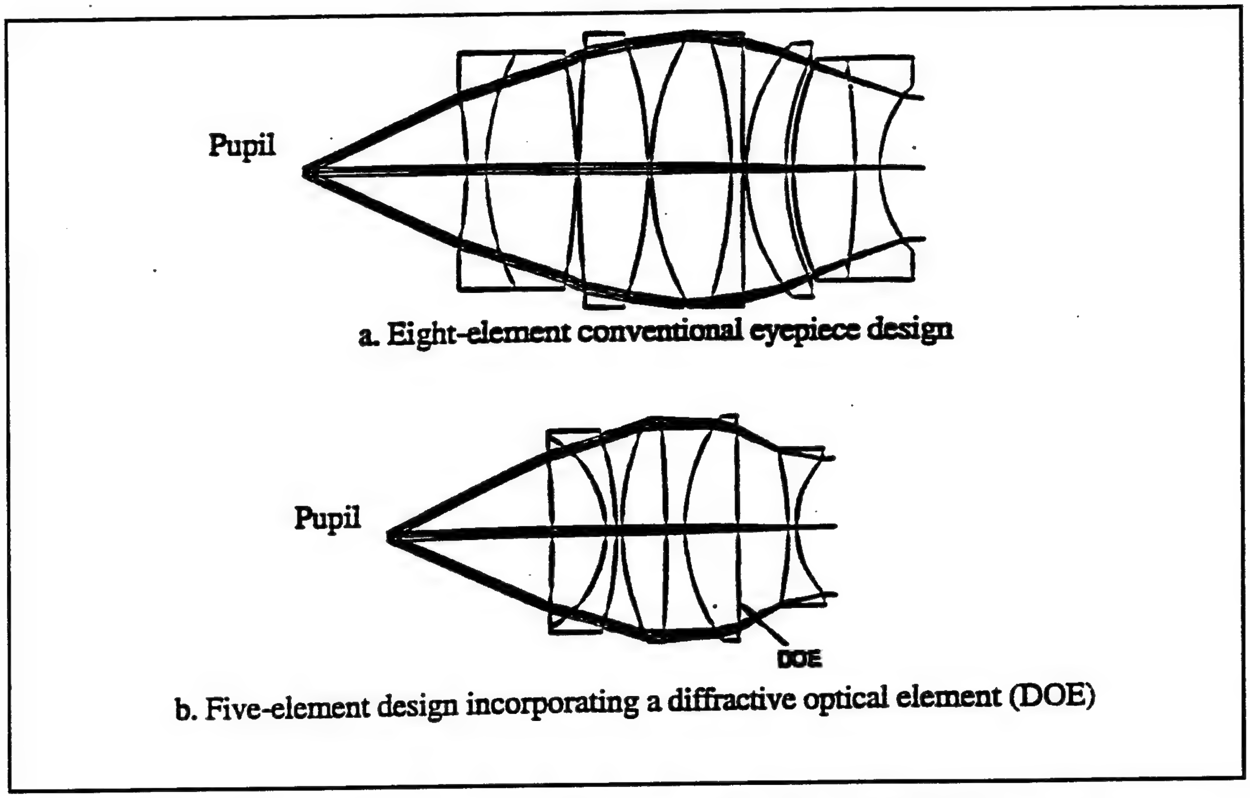

Figure 3: 50° Field-of-View Eyepiece Showing Three Fewer Elements for the Hybrid Design Compared with the Conventional Eyepiece Design. [8]

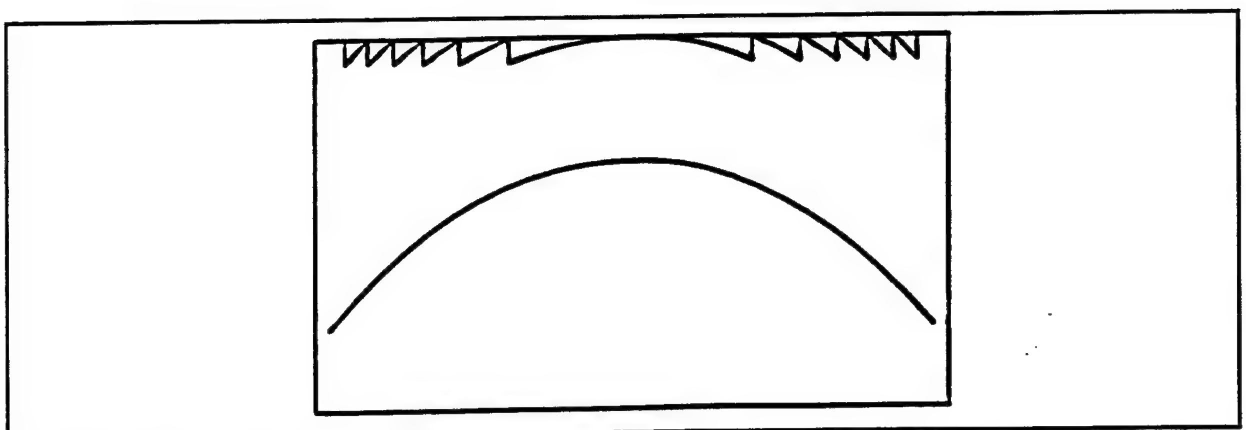

Figure 4: Phase Profile of a Kinoform (top curve) Compared with its Parent Refractive Optic (bottom curve). Neighboring zones differ in optical path difference at the image plane by one wavelength.

The state-of-the art in diamond machining has been advanced dramatically at Oak Ridge and elsewhere, and provides some key advantages over other methods for manufacturing hybrid optical elements:

- **The precision of numerically-controlled diamond turning makes possible the forming of diffractive elements on a curved lens surface**, whereas methods used in conventional binary optics production are limited to planar surfaces. As a result of this capability, both the diffractive and refractive elements can be machined in one surface simultaneously. This greatly reduces the possibility of alignment errors, requires fewer fabrication steps, and reduces fabrication time and cost.
- **Diamond turning can easiliy produce an aspheric base curve for the refractive element.** This benefit gives the designer an extra degree of freedom in the control of higher-order aberrations [11]. For example, when combined with aspheric surfaces, hybrid optics can eliminate spherical aberration and coma, while simultaneously controlling axial chromatic aberrations and spherochromatism (the variation of spherical aberration with wavelength) [8].

While diamond turning is not cost-effective for producing large quantities of a lens, the required lens shape can be produced in a suitable tooling material (e.g. electroless nickel), and this tooling can be used to produce a large quantity of molds which are then used in the sol-gel replication process at GELTECH to realize a great economy-of-scale when large numbers of optical elements are needed. In addition, diamond turning can be used effectively to produce the tools to make plastic hybrids by injection molding or also glass optics using GELTECH's precision optics molding process.

The Ultraprecision Manufacturing Technology Center at Oak Ridge National Lab houses a Nanoform 600, one of the few state-of-the-art diamond turning machines in the world. The mission of the Center is the "hands-on" deployment of manufacturing skills, which makes their partnership with GELTECH on this STTR program an ideal one. Through this proposed STTR program, hybrid optics manufacturing technology will be jointly developed for commercialization by GELTECH in Phase III.

1.3 The Sol-Gel Replication Process

1.3.1 Overall Process Description

The overall process for making molded silica optics is indicated in Figure 5 [12]. The conception of the desired optics leads to an appropriate lens design, which then defines the design of the molds to be used to produce the optical components. The manufacture of the mold requires the fabrication of a tooling which contains the microscopic relief pattern and the overall shape of the lens to be molded. For the hybrid optical elements generated in Phase I this tooling was fabricated by diamond turning. Once a tooling has been fabricated in an appropriate material it can then be used to make a large number of molds. Techniques such as photolithography or diamond turning which can be used to make mold tooling are normally too expensive for high volume production, but with the replication process the cost of the tooling is only incurred once, and can be amortized over a large volume of parts, making individual part costs low. After the mold is fabricated it is used in the sol-gel process to produce initial prototype parts. Quality control then provides necessary input to determine what, if any, minor adjustments are necessary in either the mold or processing to produce the final part.

Each different optical component requires the design of a custom mold and minor adjustments to the sol-gel process to meet the requirements of that design. These operations are performed only once, and their cost can be amortized over the total quantity of parts.

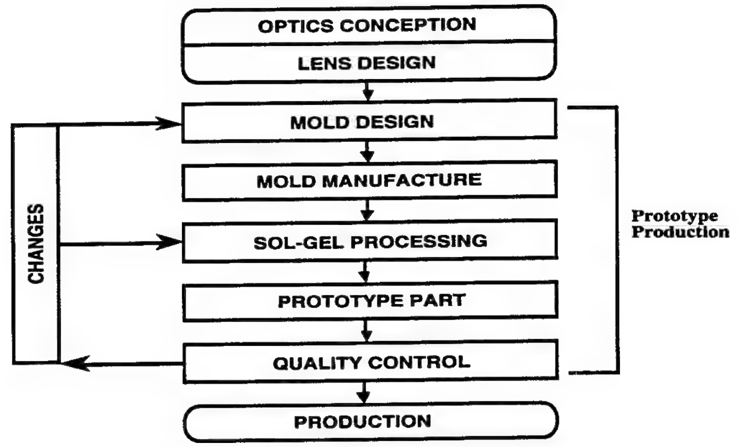

Figure 5: The Sol-Gel Replication Process

Critical to the replication process is the availability of high quality optical surfaces to be included in the molds for replication. This proposed Phase II STTR program seeks to take advantage of the unique diamond turning capabilities developed at Oak Ridge National Lab over the last 30 years to provide the required hybrid optic surface to be replicated by GELTECH. This strategy is expected to move these two technologies "from the laboratory to the marketplace".

1.3.2 Advantages of the Sol-Gel Replication Process

There are three very important advantages of the sol-gel replication process:

- **It provides a cost-effective way to produce fine-featured optical elements by casting the sol at low temperatures into molds presenting predetermined structures.** As described above, once a tooling has been fabricated in an appropriate material it can then be used to make a large number of molds. Techniques such as photolithography or diamond turning which can be used to make mold tooling are normally too expensive for high volume production, but with the replication process the cost of the tooling is only incurred once, and can be amortized over a large volume of parts, making individual part costs low.
- **The process produces optical elements in silica glass, one of the best optical materials available.** Advantages of silica include: 1) a very high transmission over the broad wavelength range of 0.2 to 3.2 microns, 2) excellent mechanical strength and hardness, 3) excellent chemical durability, 4) very low coefficient of thermal expansion, 4) excellent thermal stability, 5) excellent radiation hardness, 6) dn/dT similar to other glasses, and 7) very high laser damage threshold. These advantages make silica the material of choice for high quality optical elements, and virtually required for applications in harsh environments such as space or military uses.
- In the sol-gel replication process there is a substantial shrinkage which is controlled through processing parameters. This shrinkage has been accurately quantified and found to be very uniform in all three dimensions. **This characteristic makes it possible to fabricate parts with features smaller than those made by other processing techniques.** An additional advantage of this shrinkage is the fact that any imperfections or tool marks which are present in the mold active surface are shrunk by a factor of 2.5, which reduces scattered light at the design wavelength.

1.3.3 Sol-Gel Processing Background

The sol-gel technology for forming glasses and glass-ceramics received a great deal of attention during the last two or three decades because of the recognized advantages inherent in the method. [13-15] The sol-gel process can be divided in three major steps: 1) gel formation, 2) drying and 3) consolidation (densification, sintering). In the first step, the necessary ingredients are mixed to produce a sol. By hydrolysis and polycondensation of the sol, the three dimensional network of the future glass is formed and the solution sets into a stiff gel called a "wet gel". After an aging step necessary to develop and strengthen the initial texture of the material, the aged wet gel is dried. This crucial step consists of eliminating the interstitial liquid from the gel body. The dry gel is then heat-treated to convert the porous solid into an homogeneous glass free of porosity. The glasses manufactured by this process was developed at GELTECH, Inc. and are identified by the trade name Gelsil® [16]. An overview of the process is shown schematically in Figure 6.

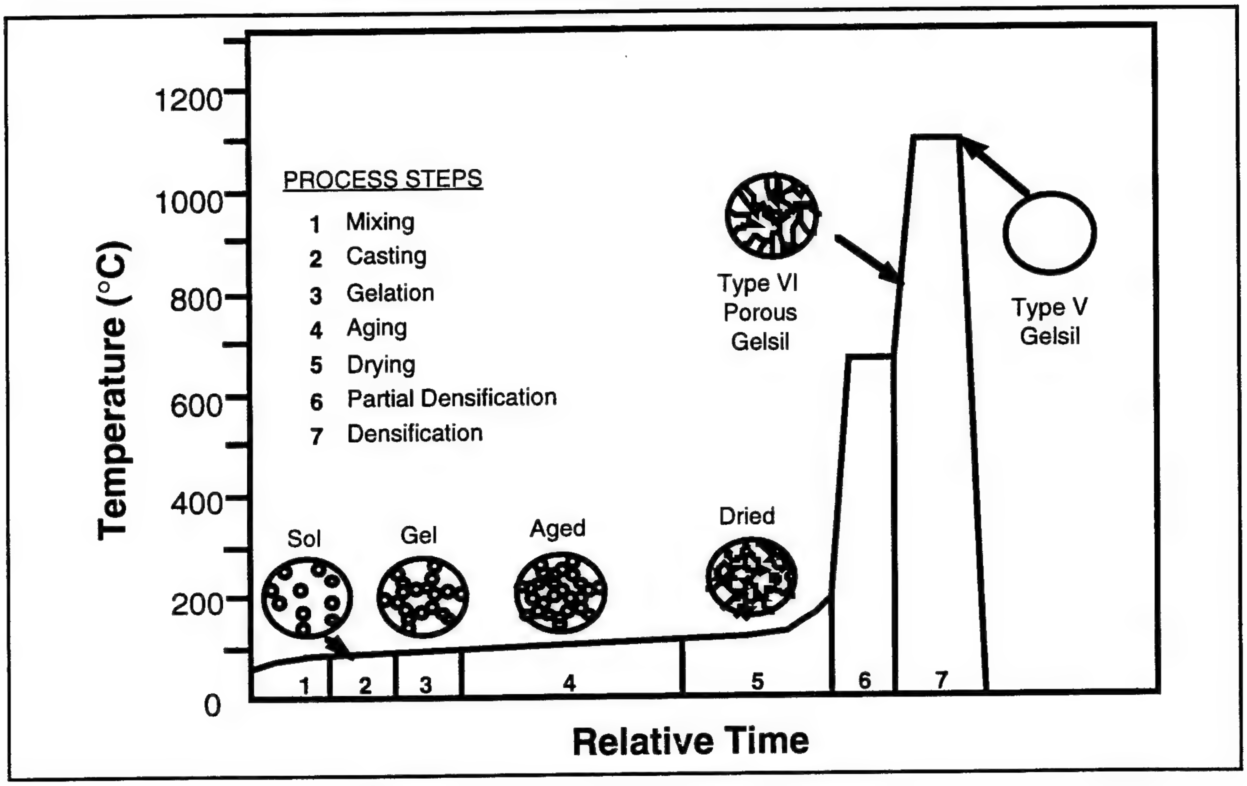

Figure 6: The Sol-Gel Process Sequence

II. PHASE I TECHNICAL OBJECTIVES

The overall goal of the Phase I research effort involved the solution of the technical challenge of fabricating a silica glass diffractive (kinoform) structure on a curved substrate using diamond turning and sol gel casting of bulk optics.

The accomplishment of this overall objective required the completion of the following technical tasks. In this section the tasks as given in the Phase I proposal are described in general terms, and in the next section the results of this development are given.

2.1 TASK 1: <u>**Design and Numerical Modeling of the Hybrid Diffractive/Refractive Optic**</u> - ORNL will utilize commercial available lens design software to design a moderately fast (f/4) lens. The lens will be numerically modeled to predict its theoretical optical performance. Other computer analysis tools, published algorithms, and custom software will be used to design the diffraction pattern for the surface of the lens. Dimensions will then be scaled up to account for the shrinkage which accompanies the replication process.

2.2 TASK 2: <u>**Fabrication of the Optic Master Using Diamond Turning**</u> - ORNL will fabricate and supply GELTECH with original diffractive masters having the diffractive pattern machined onto a curved surface. The negative of the diffractive masters will be fabricated in an appropriate material such as copper or electroless nickel-plated aluminum. After fabrication the master will be fully characterized.

2.3 TASK 3: <u>**Mold Design and Fabrication**</u> - GELTECH will fabricate the mold. It will be fabricated in two parts: 1) the active surface, which presents the desired kinoform pattern on its surface, and 2) the mold cavity which allows for filling with sol and subsequent gel removal during processing. The two areas of development, therefore, include the preparation of the active surface, which can be the master itself or a part fabricated from it, and the mold cavity design and fabrication. After fabrication, the molds will be fully characterized.

2.4 TASK 4: <u>**Fabrication of Optical Prototype Replicas**</u> - GELTECH will fabricate in this task prototypes of hybrid optics by mixing a sol, casting it into the molds prepared in task 3, and completing the sol-gel process. The existing sol-gel process will be optimized or adapted to the preparation of the prototypes. Criteria for this optimization will include the complexity of the surface designs and the mold configuration.

2.5 TASK 5: <u>**Characterization of Optical Prototypes**</u> - ORNL will characterize the prototypes for optical performance, including surface figure, freedom from aberrations, diffraction efficiency, and modulation transfer function (MTF). GELTECH will characterize the quality of the glass and of the accuracy of the replication. The techniques required for these characterizations are outlined in the following work plan.

III. RESULTS OF PHASE I

As indicated in the introduction on page nine, a 1/2" diameter glass hybrid optic has been produced according to the sequence given in the objectives above. Characterization, including optical performance testing, of these elements has been done and the results are given here. In addition, fabrication of a second hybrid optic with 5 mm diameter is in process and that work is described in section 3.6.

3.1 TASK 1: Design and Modeling of the Hybrid Diffractive/Refractive Optic - A commercial lens design program (ZEMAX-EE Optical Design Program, Focus Software Incorporated, Tucson, AZ) was used to design a hybrid singlet having the following specifications: plano convex shape, thickness of 3 mm, diameter of 12.7 mm, F/3.3. Because of the isotropic shrinkage inherent in the sol-gel casting process, the mold design must be larger than the final optic by a factor of 2.5. To make the scaling straightforward (and since a general aspheric shape is trivial for a diamond-turned optic), an even polynomial was used to specify the final design (see equation 1). Only four terms were needed to minimize the error function for the refractive portion of the hybrid optic. In general, the shape or sag of an arbitrary surface $\Delta z(\rho)$ can be expressed as:

(1) $$\Delta z = \alpha_1\rho^2 + \alpha_2\rho^4 + \alpha_3\rho^6 + \alpha_4\rho^8 + \ldots$$

where

(2) $$\rho^2 = x^2 + y^2$$

and where a right-handed Cartesian coordinate system is used to describe the optic, and light propagates along the positive z direction. Table 1 gives the coefficients of the aspheric equation for the optic, and also the coefficients scaled for the mold:

Table 1: Polynomial coefficients for the design of the prototype hybrid optic and the scaled mold pin

Coefficient for Refractive Surface	Target Design Value	Value for Scaled Mold Pin
α_1:	0.0246224	0.00984896
α_2:	$3.632985\ 10^{-6}$	$2.32511\ 10^{-7}$
α_3:	$1.326958\ 10^{-7}$	$1.3588\ 10^{-9}$
α_4:	$-1.59403\mathrm{X}10^{-9}$	$-2.61166\ 10^{-12}$

The diffractive kinoform surface is described by a general phase function, also described by a rotationally symmetric polynomial (equation 3), where λ is the design wavelength (0.58756 µm in this case). The diffractive surface needed to achromatize the hybrid does not have much optical power, and is described adequately using only the first term of the polynomial phase function.

(3) $$\Phi(\rho) = (2\pi/\lambda)\,(a1\rho^2 + a2\rho^4 + a3\rho^6 + a4\rho^8 + \ldots)$$

The final design is close to diffraction-limited, as evidenced by the modulation transfer function plot in Figure 7. Diffraction-limited performance is shown by the upper line in the MTF plot.

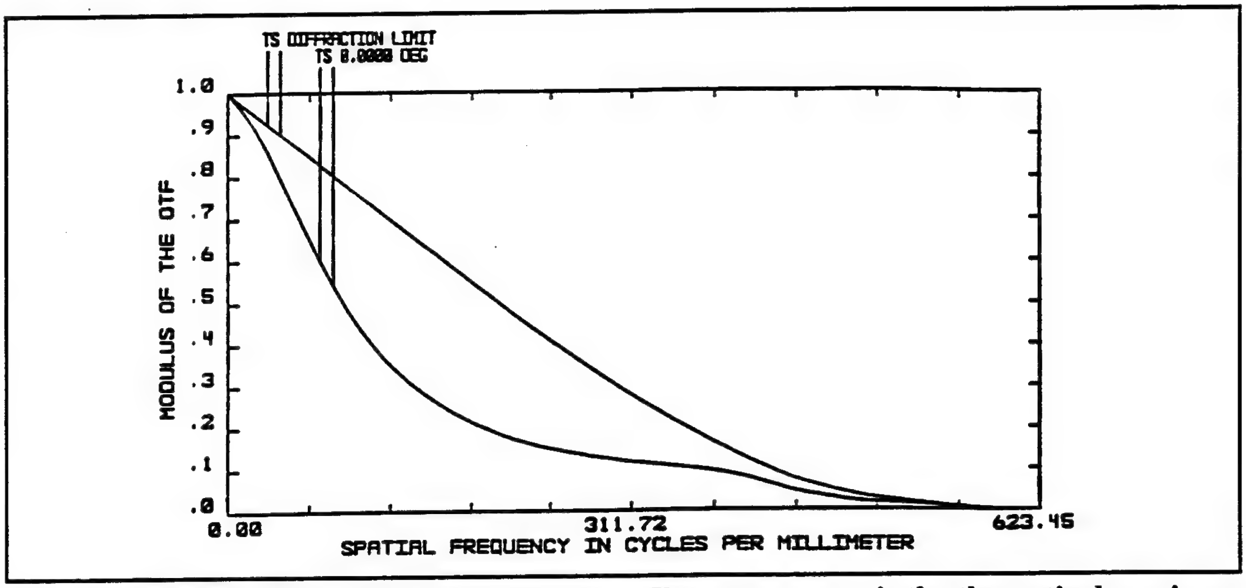

Figure 7: MTF plot of the final STTR design. The upper curve is the theoretical maximum for an ideal optic having the same F/#.

3.2 TASK 2: Fabrication of the Optic Master Using Diamond Turning

The strategy chosen for fabricating the molds was injection molding, using generic tooling which GELTECH already owned. This was expected to give optimum quality molds which lend themselves best to quantity production, both of the molds and glass optics. Using generic tooling means that only a set of mold pins was fabricated and inserted into existing tooling in order to keep the cost and lead time to a minimum. This is a strategy developed at GELTECH which allows for the production of optical plastic elements and molds at low costs. The basic steel pin was fabricated by the injection molding company that GELTECH teams with to produce other molds and plastic optics. The aspheric base curve was cut by a jig grinding company which was qualified in previous developments based on the high quality of their work. Following these steps the end of the pin was then plated at GELTECH with electroless nickel in preparation for the diamond turning of the kinoform on the curved surface. Figure 8 shows the drawing of the pin with the aspheric base curve.

The mold pin was diamond turned at Oak Ridge National Lab, and was then characterized at GELTECH using a Zygo New View® optical profilometer/interferometer. The top portions of Figures 9 and 10 show the cross-section profiles and oblique plots of the central and edge transitions of the mold pin, measured using this instrument. The measurements made on the mold pin are summarized in Table 2 and discussed in section 3.5 on the characterization of prototypes.

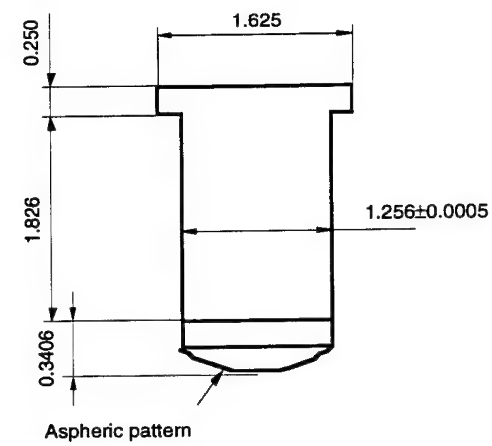

Figure 8: Mold pin to be used in injection mold tooling

3.3 TASK 3: Mold Design and Fabrication

As mentioned above, for this STTR program GELTECH used a generic mold tooling, which allows for more rapid mold fabrication and lower prototyping costs. The mold pin shown in Figure 8 was fabricated specifically to be used in one of GELTECH's preexisting toolings. After fitting the pin the molds were sampled and characterized at GELTECH to ensure a good quality replication. Using the optimum injection molding parameters known at that time, a production order was run to obtain a larger quantity of molds for use in the production of molded silica glass prototypes. The central portions of Figures 9 and 10 show the cross-section profiles and oblique plots of the central and edge transitions of the mold. As can be seen from comparison with the mold pin at the top of the figures, the replication of the optical surface of the mold pin by the plastic was very good, but as expected there was some small percentage of fidelity loss in the outer transitions. For comparison, the bottom portions of Figures 9 and 10 show the same plots for an as-cast silica glass hybrid optic, and a summary of actual measurements taken from the mold pin, plastic mold, and glass part is given in Table 2 and discussed in section 3.5 on the characterization of prototypes.

Interferometric testing of the molds was not a trivial matter, since they have both an aspheric curvature and the diffractive features on the surface. The aspheric nature of the molds causes the fringes to be so close together over the outer 50% of the aperture that the software is unable to resolve them. To alleviate this problem a special null optic would have to be fabricated. However, over the measurable area it was possible to identify some astigmatism in the molds, which as described below was noticed in the optical performance of the hybrid optics produced from them. A second sampling of the molds was done in an attempt to improve mold quality. Five cycles were run on the molding machine, varying molding parameters such as time and temperature. These were then analyzed the same way by interferometry. Of the five cycles, one did give improved results, i.e. reduced astigmatism. However, further discussions with the molding company have indicated that there are further steps which can be pursued, and these steps are planned for the near future.

3.4 TASK 4: Fabrication of Prototypes

Glass prototypes were produced by means of the sol-gel process, as described in section 1.3. parts were cast as part of four batches to produce a net yield (before individual inspection) of 86%. Preliminary data indicates that about half of the parts produced are currently of optical quality good enough to be measured. The next section gives specific data on optical performance and surface profiles of the glass hybrid optics.

3.5 TASK 5: Characterization of Prototypes

Glass prototypes were characterized by several methods, and the results are given here:

a) Surface profile measurement - Using the New View 100® (Zygo Corporation) a surface profile was obtained, and measurements were made of the width and depth of the transitions at both the center and edge of the optical pin, the plastic molds, and the final glass parts. Cross section and oblique plots are given in Figures 9 and 10. Quantitative data is summarized in Table 2. (Width of edge transitions is not reported due to difficulty in maintaining one-to-one correspondence. A method to maintain this will be devised in Phase II.)

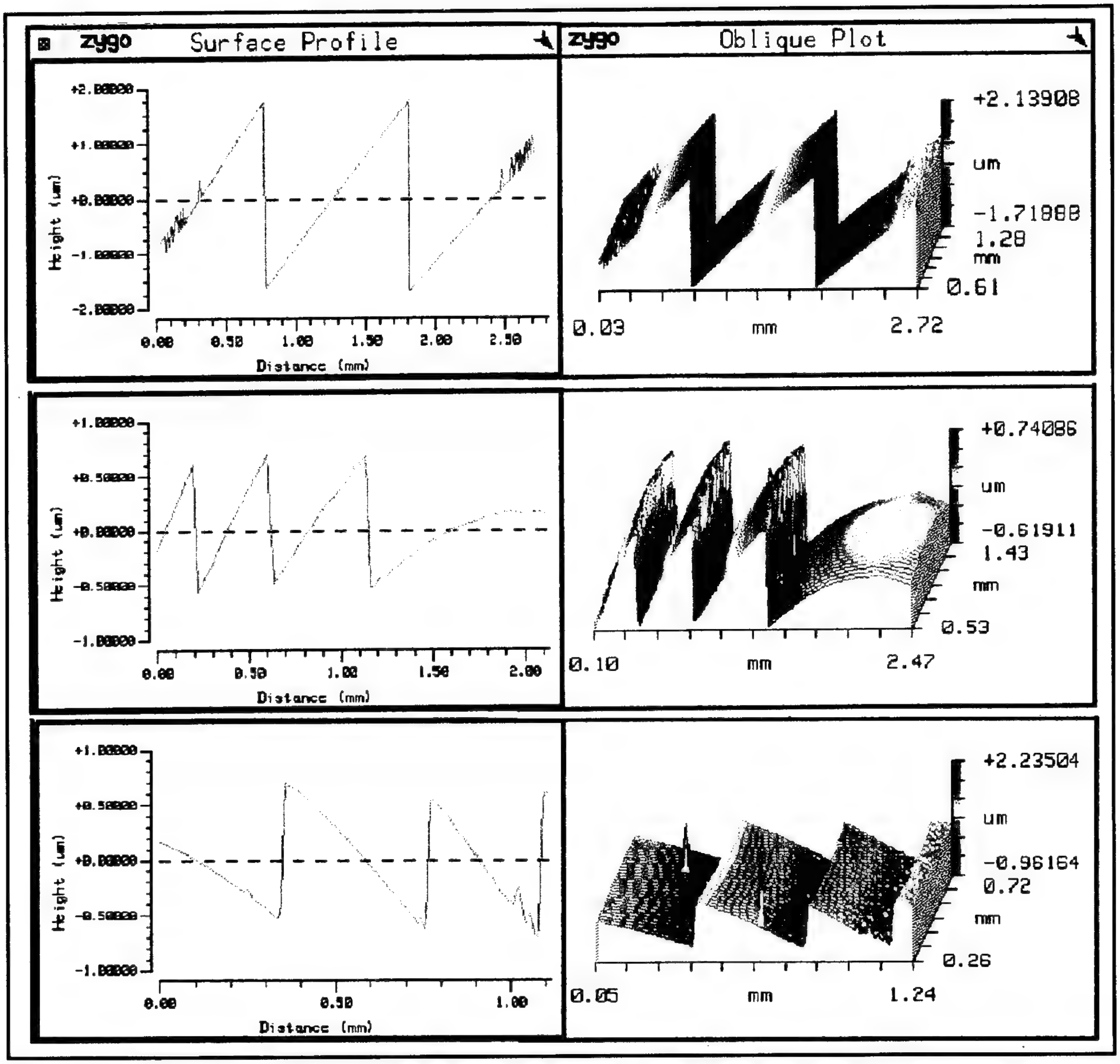

Figure 9: Profile and Oblique Plot of Central Transitions for the Diamond Turned Mold Pin (top), Plastic Mold (center) and Glass Hybrid (bottom)

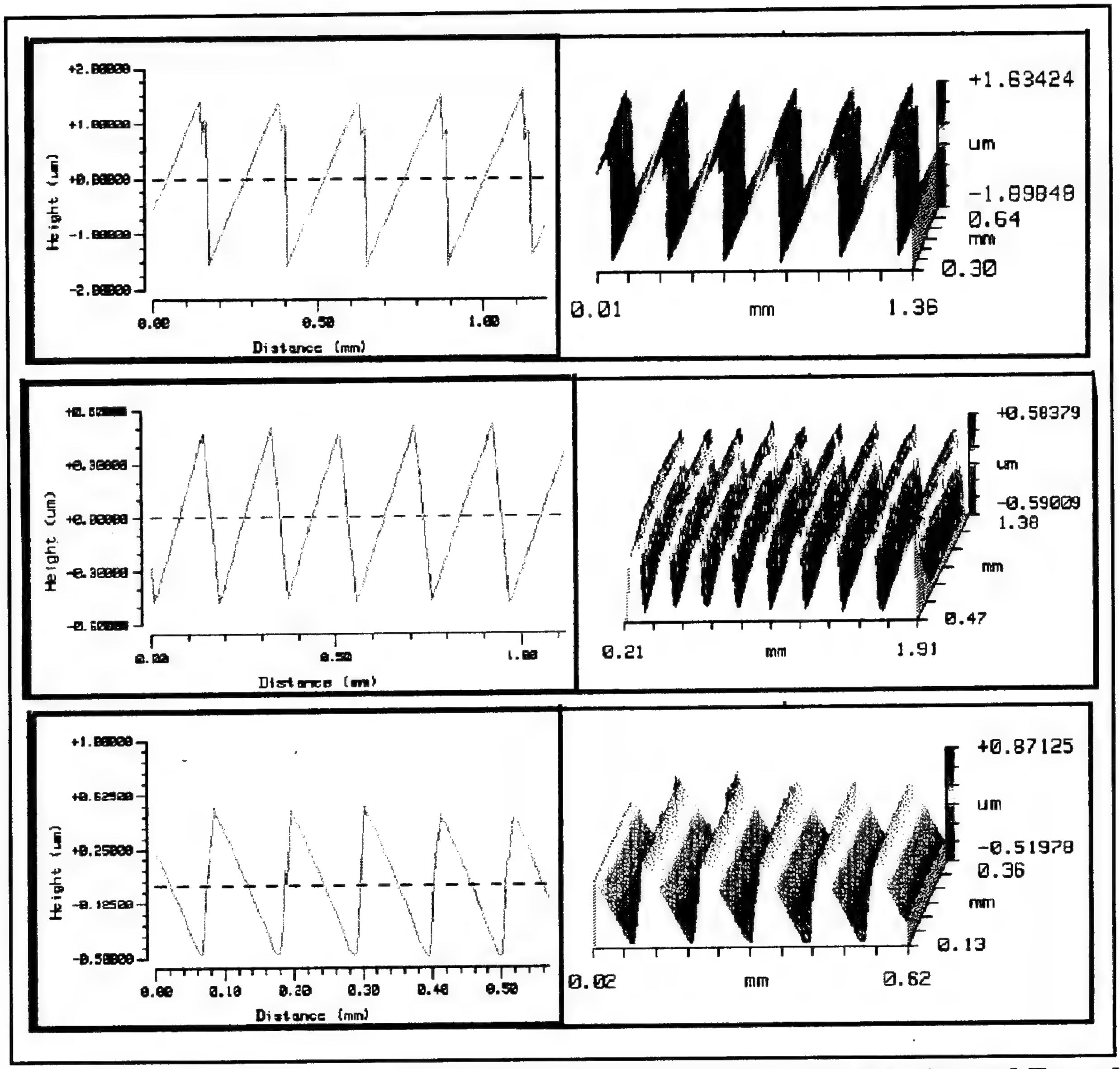

Figure 10: Profile and Oblique Plot of Edge Transitions for the Diamond Turned Mold Pin (top), Plastic Mold (center) and Glass Hybrid (bottom)

Table 2: Surface Profile Measurements of Kinoform Surfaces of Master, Mold, and Glass Hybrid Prototype

	Optical Pin		Plastic Mold		Glass Prototype	
	Width (µm)	Height (µm)	Width (µm)	Height (µm)	Width (µm)	Height (µm)
Center Transitions	1.02	3.41	1.00	3.47	0.40	1.33
Edge Transitions	NA	2.90	NA	2.65	NA	1.00

b) Optical performance testing was done on a hybrid optical element using a Zygo interferometer. The total wavefront distortion error over 80% aperture was measured to be about **3.6 waves peak-to-valley, and about 0.72 waves rms.** This level was typical for about half of the parts produced. Because the interferometer presently available at GELTECH is a fringe measurement device it was not possible to obtain measurements on the remaining parts. The interferometric results indicate some astigmatism in the optic, which may be due to either the molds or the glass molding process. In Phase II one key task will be to make a quantity of highly precise molds to be able to isolate this problem and hopefully eliminate its source. Figure 11 shows an interferogram of the optical performance measured with a Zygo PTI interferometer.

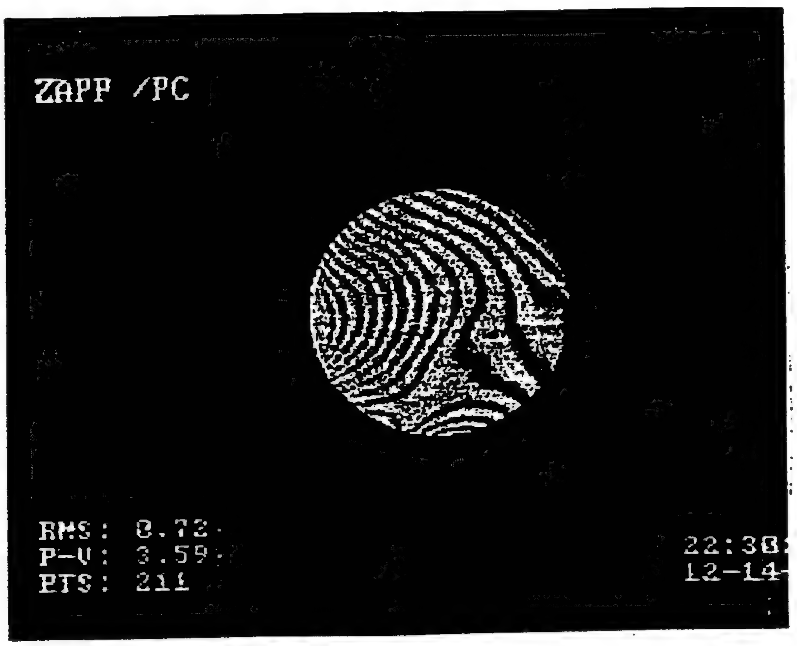

Figure 11: Interferogram Showing Measured Optical Performance of the Silica Glass 1/2" Hybrid Optic

Additional testing was done on the glass hybrid to get an idea how the lens performed at a smaller aperture. Although this changes the f/# of the lens, it can give some information about the process and part quality. The results at approximately 50% aperture were much better than at 80%. **Transmitted wavefront error was about one wave peak-to-valley, and about 0.25 waves rms.** This result is not surprising. Other results at GELTECH on traditional spherical plano-convex lenses to date have indicated that better performance is achieved with smaller diameters. At the present time a 5 mm hybrid lens is being produced to further quantify the size effect.

c) Modulation Transfer Function measurements were done at Optikos, Inc. and the results are given in Figure 12. Although the design was near diffraction limited, the performance of these first prototypes was not expected to be near that quality, since the total wavefront error measurements indicated, as mentioned above, about three waves peak-to-valley and 0.7 waves rms. The double lines indicate an astigmatism in the lens, which is attributed at least in part to the astigmatism observed in the molds.

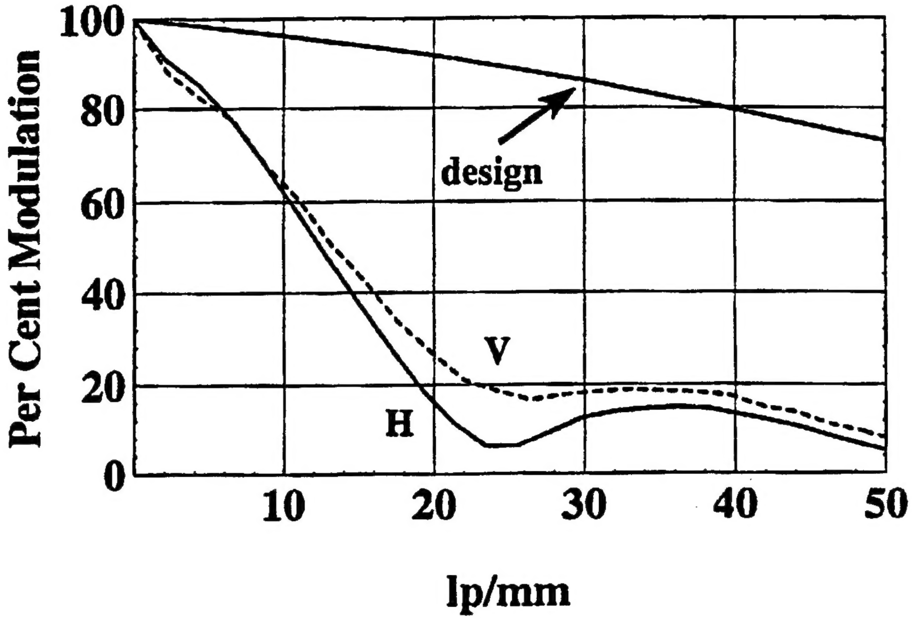

Figure 12: Modulation Transfer Function Plots for 1/2" Hybrid Optical Element On-Axis at 80% Aperture

d) Diameter measurements were done as additional quality control on several molds and glass lenses. The data is given in Table 3:

Table 3: Diameter Measurements of Hybrid Optic Molds and Lenses

	Hybrid Mold	Silica Glass Optic
Diameter (mm)	31.54	12.62
Standard Deviation	0.0162	0.0443
% Variation	0.05	0.3
Sample Size	24	14

3.6 Development of a 5 mm Hybrid Optic

Initial results from the 1/2" diameter hybrid indicated that going to a smaller diameter should give improved optical performance. Also, data collected from molding simple plano convex lenses by the sol-gel process has indicated that smaller diameters give improved optical performance. For these reasons a 5 mm hybrid was designed, a mold pin was fabricated, and molds were sampled and tested optically. The results to date are as follows:

a) Modeling of the optical design of the 5 mm diameter optic gave essentially diffraction limited performance, which is an improvement over the 1/2" design.

b) Fabrication of the optical pin was successful, even though it was substantially smaller in diameter than the previous pin and represented one of the smallest hybrid profiles fabricated on the diamond turning machine at Oak Ridge National Lab. Measurement of the surface profiles of the kinoform was done using the Zygo NewView100®. This data was used for comparison with the molds formed from it.

c) The first sampling of molds from this optical pin indicated that the replication of the kinoform was initially not as good as the replication of the larger 1/2" optical pin. The plastic was not filling the diffractive features on the pin surface completely. As a result a tooling modification was made and the molds were resampled. This modification made a significant improvement in the quality of the replication. The replication of the small kinoform features on the nickel pin was excellent. Furthermore, interferometric testing of these molds indicated no measurable astigmatism, which is a good improvement over the 1/2" molds. A large quantity of molds has since been ordered and these will be cast in the sol-gel process upon receipt. Already, this second iteration shows improvement because of lessons learned on the first lens.

IV. SUMMARY AND CONCLUSIONS

The results of Phase I indicate that the feasibility of fabricating a silica glass diffractive (kinoform) structure on a curved substrate using diamond turning and sol-gel casting of bulk optics has been demonstrated. Several important conclusions can be drawn from the work to date:

a) A first hybrid diffractive/refractive optic has been produced successfully by a unique combination of diamond turning, injection molding, and bulk casting through a sol-gel process.
b) The silica glass hybrid is corrected for spherical and chromatic aberrations in one element, one glass type.
c) The optical performance of the elements achieved to date is three to four waves peak-to-valley, and 0.7 waves rms (80% clear aperture).
d) Modulation transfer function measurements indicate astigmatism in the lens, believed to be due, in part, to astigmatism observed in the molds.
e) Although the optic is not near diffraction limited, it represents a successful first attempt at fabricating such a lens, with promise for further improvement in a Phase II program.
f) Because the sol-gel process has been shown to give better optical performance in smaller diameter elements, a second hybrid is currently under development. Molds for these have been optimized and will be run in production soon.
g) The produced prototypes represent the first hybrid component having potential application in the visible and ultraviolet regions.
h) Development of the hybrid technology for the sol-gel replication process has indicated the possibility for other spinoffs, including plastic hybrid optics by injection molding and other glass hybrid optics by a high temperature glass pressing technology now used at GELTECH for making high precision aspheres.

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